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# SPECTRAL DEVELOPMENT OF A SOLAR X-RAY BURST OBSERVED ON OSO-7

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# Spectral Development of a Solar X-Ray Burst Observed on OSO-7

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13. ABSTRACT

We have made computer fits to proportional counter soft x-ray data and scintillation counter hard x-ray data for a small hard x-ray burst at UT 0519 on November 16, 1971. The energy content of the thermal plasma increased in conjunction with a hard x-ray burst of 60-second duration which entirely preceded the 5-keV x-ray maximum. If x-rays arise by thick target bremsstrahlung, the observed suprathermal electrons have sufficient energy to heat the thermally emitting plasma. In the thin target case, the collisional energy transfer from nonthermal electrons suffices only if the power law electron spectrum is extrapolated below 10 keV or the ambient plasma density exceeds $4 \times 10^{10}$ cm$^{-3}$.

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## FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-72-C-0073.

This report, which documents research carried out from January through April 1972, was submitted 19 October 1972 to Lieutenant Colonel Elliott W. Porter, DYA, for review and approval.

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Approved

G. A. Paulikas, Director
Space Physics Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

ELLIOTT W. PORTER, Lt Col, USAF
Asst Dir, Development Directorate
Deputy for Technology

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# I. INTRODUCTION

The continuum radiation observed in solar x-ray bursts can be divided into two categories. At energies below about 10 keV, "thermal" emission—from a plasma assumed to have a Maxwellian electron distribution with temperature T and "emission measure" (EM) $n_e n_i V$—dominates the spectrum, while at higher energies the spectrum is conventionally represented as a power law of the form $F(h\nu) = A(h\nu)^{-\gamma}$ where $F(h\nu)$ is the flux in photons/ ($cm^2$-sec-keV). The latter component is often not present at detectable levels. To date, most spectral measurements have concentrated on either the low energy component (Culhane and Phillips 1970, Kahler, Meekins, Kreplin, and Bowyer 1970) or the high energy component (Frost 1969, Kane and Anderson 1970). Because of the steepness of the low energy spectrum, attempts to cover the entire x-ray range with a single detector have been plagued by pulse pileup and saturation effects (Kane and Hudson 1970). The UCSD solar x-ray instrument on OSO-7 uses a proportional counter with a 0.32 $cm^2$ window having an $e^{-1}$ cutoff at 4 keV for measurements below 15 keV and a 9.6 $cm^2$ sodium iodide [NaI(Tl)] scintillation counter with an $e^{-1}$ window cutoff at 10 keV for higher energies (Harrington, Maloy, McKenzie, and Peterson 1972). Use of two detectors allows simultaneous measurement of the thermal and nonthermal burst components. We discuss here a small hard x-ray burst on November 16, 1971. At the time of writing observations over other frequency ranges are not available, but the burst is typical of those usually associated with subflares and weak, if any, impulsive microwave bursts. Following a description of the burst, we compare the energy in suprathermal electrons as evidenced by hard x-ray emission with that needed to heat the thermally emitting plasma using two possible models to explain the rapid decay of high energy x-ray emission.

## II. DATA

The UCSD solar x-ray experiment occupies one segment of the rotating wheel section of OSO-7. The detectors have apertures of 90° parallel to by 20° perpendicular to the wheel plane. Since the wheel rotation period is about 2 seconds, each spectrum, accumulated over 10.24 seconds, consists of data from five or six 0.5-second solar exposure periods. The proportional counter has eight logarithmically spaced energy channels in the 2-15 keV range and the scintillator has nine logarithmically spaced channels between 10 and 320 keV. Data for all channels are accumulated and transferred simultaneously and read out in turn to the spacecraft telemetry system.

Figure 1 shows plots of counting rate versus time for three proportional counter and three NaI detector channels for November 16, 1971. At 5 keV the x-ray burst under discussion started at UT 0516, reached a peak at 0521, and decayed slowly thereafter. A burst of x-rays extending to photon energies greater than 30 keV commenced at UT 0518.6 and lasted until 0519.6. Following the usual pattern for such events (Kane and Anderson, 1970), the nonthermal burst first hardened then softened spectrally and was completely undetectable above 30 keV at the time of the maximum 5-keV flux. Figure 2 shows three spectra, during the hard x-ray burst, accumulated over the basic 10.24 second time interval. The plotted data points have been corrected for detector area, efficiency, and live time. We have made computer least square fits to the proportional counter data for thermal spectra and to the NaI detector data for power law spectra. The proportional counter fits use data from five channels between 5.1 and 14.5 keV, and the NaI fits use three (13.5-44 keV) or, when available, four channels (13.5-64 keV). The thermal fits take account of free-free and free-bound emission using the approximation of Culhane and Acton (1970). Fits incorporating a correction for iron line emission around 6.6 keV did

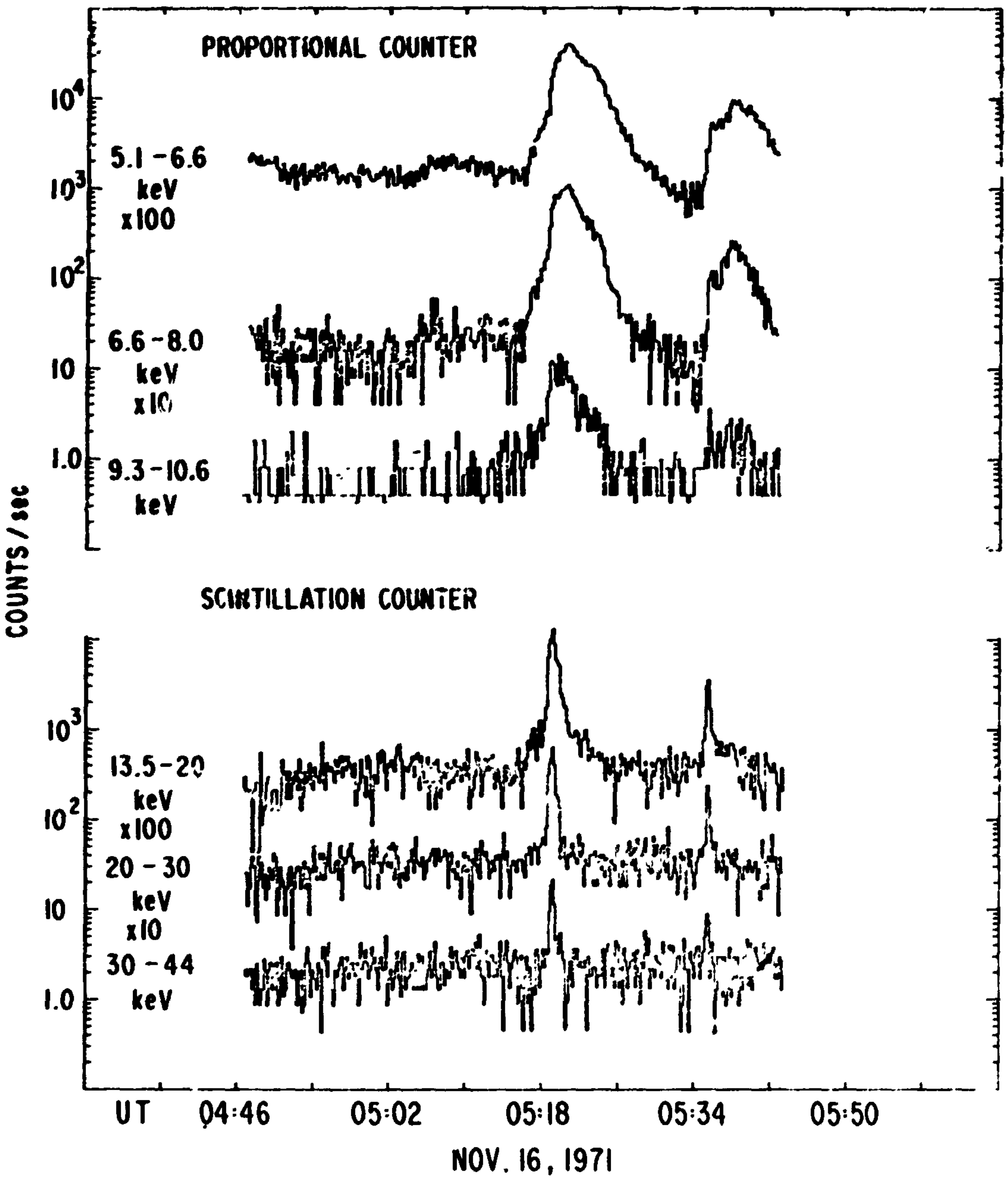


Figure 1. X-ray Counting Rates With a 10.24 Second Time Resolution as a Function of Time and Energy Observed on November 16, 1971. This paper treats the earlier of the two bursts shown.

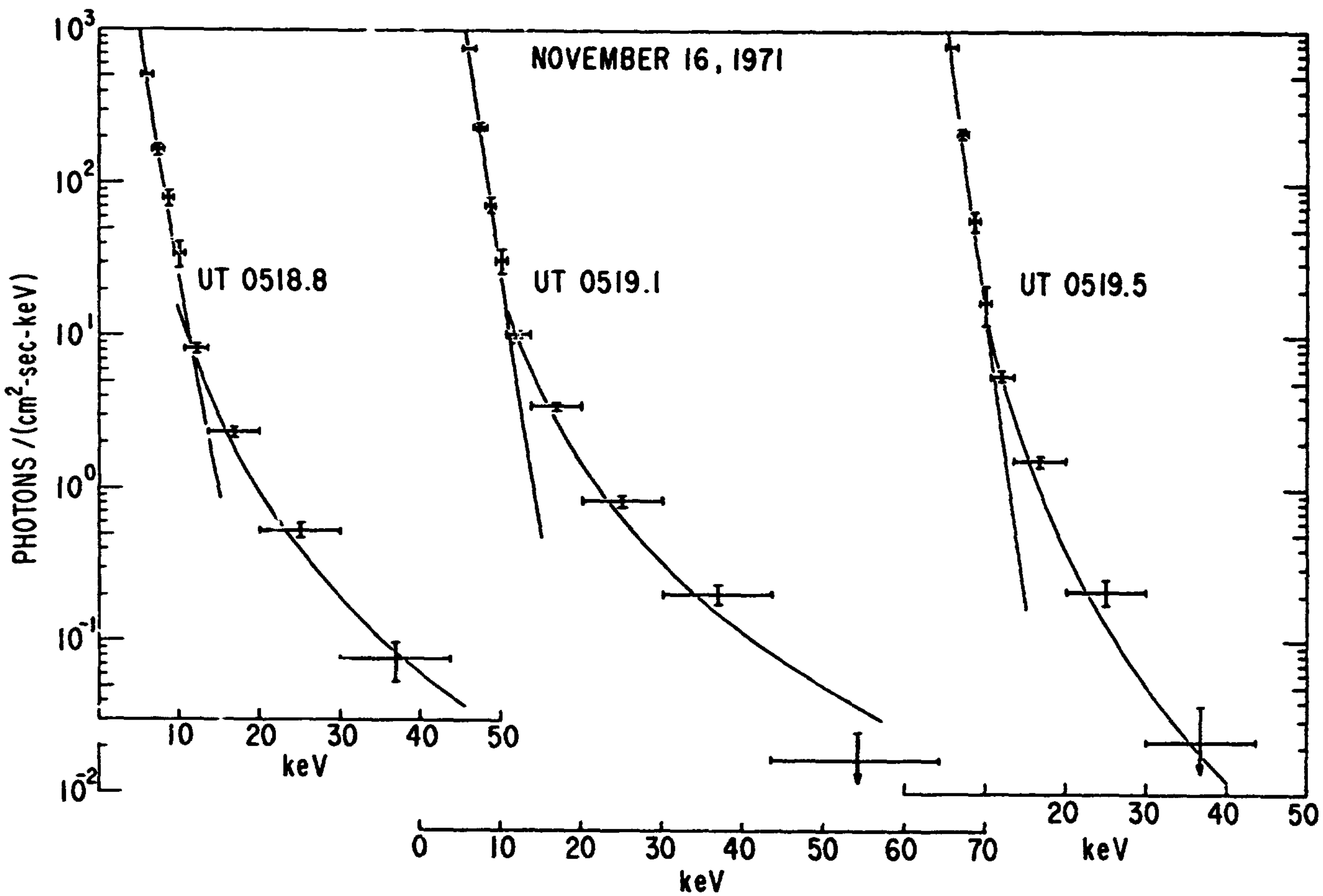


Figure 2. Corrected Spectra Taken During the Hard X-ray Burst Illustrating the Departure From Thermal Spectra at High Energies and the Characteristic Hardening Then Softening of the Nonthermal Spectrum. Each illustrated spectrum represents about 2.5 seconds of data accumulated during a 10.24 second period.

not differ importantly from those presented here with no such correction. The curves drawn in Figure 2 represent the best fits to the plotted data. Differences between the curves and plotted points are due to finite detector resolution which is not taken into account in plotting. Figure 3 summarizes the analysis of spectra during the nonthermal burst.

The thermal burst behaved much like those discussed by Kahler et al. (1970) and Horan (1971). A maximum temperature of about $20 \times 10^6$ °K was reached early in the burst at 0518.8, and the temperature decreased thereafter. Meanwhile the emission measure increased so that soft x-ray flux increased despite the declining temperature. At the time of maximum 5 keV emission, T was $13 \times 10^6$ °K and the emission measure was $7 \times 10^{47}$ $cm^{-3}$. Energy input to the soft x-ray emitting region apparently continued even beyond this time, but increasing emission measure could not compensate for decreasing temperature and x-ray flux decayed.

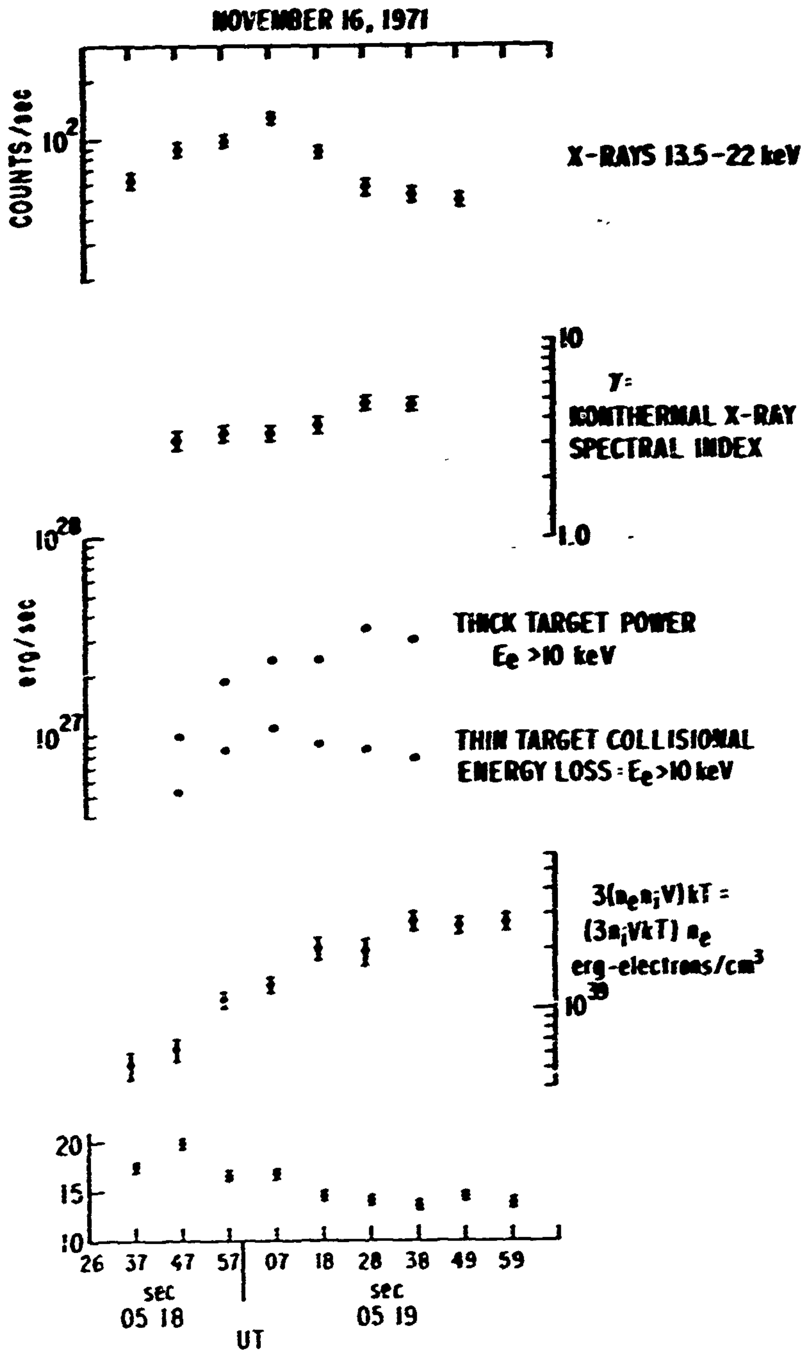


Figure 3. Plots of Various Physical Quantities Derived from the Data. The x-ray flux plotted in the top curve provides a reference to the hard x-ray burst. The next three plots are derived from a scintillation counter data, and the bottom two are derived from proportional counter data.

## III. ENERGETICS

High energy electrons accelerated during solar flares are observable through their x-ray emission for only short periods of time. Kane and Anderson (1970) noted that decay times are much too short to be explained by radiation energy loss. Two plausible mechanisms remain. In one case the electrons rapidly transfer their energy to the medium through collisions or plasma collective interactions, and in the second case decay is dominated by escape of suprathermal electrons to a region in the corona where density is low enough that bremsstrahlung does not occur at detectable levels.

### A. THICK TARGET CASE

Takakura and Kai (1966) have shown that if collision dominates the decay, higher energy electrons should be longer lived, but Kane and Anderson (1970) have noted that more energetic x-ray emission is shorter lived. This observation is confirmed by data from OSO-7. This means that energy loss must occur so rapidly that even for the highest energy electrons observed, the decay is fast compared with the time required for a spectral measurement, and the time behavior of the x-ray emission reflects that of the acceleration itself. This implies that $t_t$, the time required for an electron to lose its energy via collisions (Trubnikov 1965), must be less than the data accumulation period. Thus for OSO-7,

$$t_t = \frac{6.3 \times 10^{-20} v^3}{n_e} < 10.24 \text{ seconds.} \tag{1}$$

For an electron kinetic energy, $E_e$, of 50 keV, we have $n_e > 10^{10}$ cm$^{-3}$. For the data of Kane and Anderson (2.3 second time resolution, maximum $E_e \sim 100$ keV), $n_e > 10^{11}$ cm$^{-3}$ if collisions dominate the decay and collective effects are negligible. In this case we have a thick target x-ray spectrum in which photons are emitted by each electron from the moment of its injection or acceleration until it has lost essentially all its energy.

Brown (1971) has developed formulas for treating thick target bremsstrahlung spectra. If the x-ray flux spectrum has the form

$$F(h\nu) = A(h\nu)^{-\gamma} \text{ photons}/(\text{cm}^2\text{-sec-keV}), \tag{2}$$

the accelerated or injected spectrum is a power law with spectral index $\delta = \gamma + 1$. From Brown's results the power input in the form of kinetic energy of electrons above $E_c$ keV, where $E_c$ is a low energy cutoff in the electron spectrum, is

$$P_{thick}(E_c, \delta) = 4.29 \times 10^{24}\, A\gamma^2(\gamma - 1)\, B\left(\gamma - \frac{1}{2}, \frac{3}{2}\right) E_c^{-(\gamma-1)} \text{ erg/sec}, \tag{3}$$

where B(x, y) is the Beta function.

From the thermal fits we can derive an estimate of the energy content of the thermally emitting plasma:

$$U = 3n_e VkT = \frac{3(EM)\,kT}{n_e} \text{ erg.} \tag{4}$$

The product, $U \times n_e$, plotted in Figure 3 is directly derivable from the soft x-ray spectrum. During the ~60 seconds of significant x-ray emission above 30 keV, $U \times n_e$ increased by $2.2 \times 10^{39}$ erg-electrons/cm$^3$. If the ambient density was $10^{11}$ cm$^{-3}$, the low energy electron spectrum cutoff, $E_c$, could be as high as 21 keV and the suprathermal electron kinetic energy would still supply sufficient energy to account for the observed increase in U. Conversely, if $E_c = 10$ keV, sufficient energy is available if $n_e > 1.5 \times 10^{10}$ cm$^{-3}$. This criterion is certainly satisfied whenever the thick target conditions above are valid. It is clear that almost any power law electron spectrum can contain an arbitrary amount of energy if it is extrapolated to low enough energies. Since the thermal and power law spectra coincide at about 10 keV, below this energy the distinction between thermal and non-thermal becomes obscure. Therefore we believe that $E_c$ should not be assumed to be lower than 10 keV in evaluating a collisional heating model.

## B. THIN TARGET CASE

If escape dominates the hard x-ray burst decay, the x-ray spectrum arises from a population of electrons whose spectrum is unchanged from the acceleration or injection spectrum. The collisional energy loss of an electron is (Takakura 1969)

$$\frac{dE_e}{dt} = 4.9 \times 10^{-9}\, n_e E_e^{-1/2}\ \text{keV/sec.} \tag{5}$$

For the power law x-ray spectrum, the instantaneous nonthermal electron spectrum is

$$n(E_e) = A' E_e^{-\alpha}\ \text{electrons/(cm}^3\text{ - keV)}, \tag{6}$$

where $\alpha = \gamma - 1/2$ and (McKenzie 1972)

$$A' = \frac{1.05 \times 10^{42} (\gamma - 1)\, A}{n_e V}. \tag{7}$$

Integrating equation (5) over the spectrum of equation (6) gives the total collisional energy transfer during a time interval $\Delta t$:

$$P_{thin}\, \Delta t = 8.19 \times 10^{24}\, A E_c^{-(\gamma - 1)}\, \Delta t\ \text{ergs}, \tag{8}$$

where we again invoke the low energy cutoff, $E_c$. For $E_c$ = 10 keV we find that the collisional energy transfer during the period of 30 keV x-ray emission was $5.2 \times 10^{28}$ ergs. If this is to be sufficient to heat the thermal x-ray source, the density in the region must be greater than $4 \times 10^{10}$ $cm^{-3}$. Although this may be high enough for the thick target conditions to be satisfied, if the characteristic time for escape is less than $t_t$, the thin target picture is the more valid one.

## IV. DISCUSSION

We have considered the collisional energy transfer from energetic electrons to the ambient plasma in two possible situations. In the thick target case there is apparently ample energy in the electrons observed by their bremsstrahlung to heat the soft x-ray emitting region. No extrapolation of the power law to lower energies is necessary. In the thin target case the collisional energy transfer suffices only if the power law spectrum is extrapolated below 10 keV or the density is higher than $4 \times 10^{10}$ cm$^{-3}$. The thin target case also raises the interesting possibility that most of the energy available in the form of electron kinetic energy escapes to a low density region in the corona where energy loss takes place too slowly to yield x-rays at detectable levels. In that case the observable flare phenomena might reveal only a fraction of the energy actually available in energetic electrons.

While the thin target case allows a great deal of speculation with little hope of proof or contradiction, the thick target case appears to be more manageable in terms of observables. What is required is a large sample of events showing excellent time correlation between energy input to the thermally emitting region and hard x-ray emission indicative of energy loss by energetic electrons. Having this in hand one should then attempt a detailed energy balance for as many flares as possible. For the present event the possibility exists that collisional energy loss provides more energy than can be accounted for by other observed phenomena. A blast wave like those detectable in the interplanetary medium following major flares might account for much of the apparent energy excess. The OSO-7 experiment should provide a good sample of bursts for the required analysis, and we plan a more complete study later.

Finally, we should mention that collisional energy transfer is probably not the only flare heating mechanism. Large soft x-ray bursts, many of them impulsive, do occur in the absence of detectable nonthermal emission. We recall that, during the November 16 event discussed here, the product $U \times n_e$ continued to increase after the disappearance of x-ray emission above 30 keV. Coppi and Friedland (1971) have discussed a model in which the early explosive phase in which bursts of nonthermal runaway electrons are produced is followed by a phase of heating due to a large turbulent resistivity. Thus unobserved nonthermal electrons do not have to be invoked for heating late in flare development.

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